GSFC VLBI Analysis Center Report

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Abstract This report presents the activities of the GSFC VLBI Analysis Center during 2013. The GSFC VLBI Analysis Center analyzes all IVS sessions, makes regular IVS submissions of data and analysis products, and performs research and software development aimed at improving the VLBI technique.

1 Introduction

The GSFC VLBI Analysis Center is located at NASA's Goddard Space Flight Center in Greenbelt, Maryland. It is part of a larger VLBI group which also includes the IVS Coordinating Center, the CORE Operation Center, a Technology Development Center, and a Network Station. The Analysis Center participates in all phases of geodetic and astrometric VLBI analysis, software development and research. We maintain a Web site at http://lupus.gsfc.nasa.gov. We provide a pressure loading service to the geodetic community at http://gemini.gsfc.nasa.gov/results/aplo and a new ray tracing service. We provide additional services for hydrology loading, nontidal ocean loading, and meteorological data. These services can be found by following the links on the GSFC VLBI group Web site: http://lupus.gsfc.nasa.gov/dataresults_main.htm.

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2. NVI, Inc./NASA Goddard Space Flight Center

GSFC Analysis Center

IVS 2013 Annual Report

2 Analysis Activities

The GSFC VLBI Analysis Center analyzes all IVS sessions using the *Calc/Solve* and *νSolve* systems, and performs the *fourfit* fringing and *Calc/Solve* analysis of the VLBA-correlated RDV sessions. The group submits the analyzed databases to IVS for all R1, RDV, R&D, APSG, AUST, INT01 and INT03 sessions. During 2013, GSFC analyzed 163 24-hour sessions (52 R1, 50 R4, six RDV, ten R&D, five AUST, three APSG, seven EURO, five T2, five OHIG, eight CRF, five CRDS, and seven JADE) and 333 one-hour UT1 sessions (243 INT01, 53 INT02, and 37 INT03), and we submitted updated EOP and daily Sinex files to IVS immediately following analysis.

3 Research Activities

- Intensive (IVS-INT01) Scheduling: We continued to study the Uniform Sky Strategy (USS), an alternative INT01 scheduling strategy proposed and tested in 2009/2010 and used for the INT01s on alternating days since mid-2010. We focused on refining the USS to address ways in which it underperforms the original scheduling strategy. We investigated the effects of schedule characteristics (e.g., temporal distribution of the observations) on schedule metrics (e.g., protection against random noise). We also investigated changing the schedule characteristics, and in turn the metric values, by passing new parameter values to program *sked*.
- Source Monitoring: Together with USNO we continued monitoring all ICRF2 defining sources and all good geodetic sources, and this year we

added the Gaia transfer sources. The goal is to observe all geodetic and Gaia transfer sources 12 times/year and the remaining ICRF2 defining sources five times/year. The R1, R4, and RDV sessions participate in the source monitoring program.

- Good Geodetic Source Catalog: Good geodetic sources are scarce. In 2011, many were removed because of time variability of their positions (special handling sources). In 2013, there were 266 geodetic sources in the good geodetic catalog. To search for additional sources, we used an approach similar to that described by Jing Sun (Shanghai Astronomical Observatory) in her PhD thesis. Our criteria was as follows: a structure index (SI) less than or equal to 2.5 (701 sources in IERS Technical Note No 35, Table 1) and an X-band flux greater than 0.25 Jy (658 sources in flux.cat). Of the 152 sources meeting both criteria, 105 were already in the good list and 47 were not. We wrote a proposal to observe these 47 sources in R&D sessions to verify if they could be detected and to measure their fluxes. They were observed in RD1302, RD1303, and RD1304. After analysis, 35 were found to be suitable and were added to the good geodetic source catalog.
- Gaia Transfer Sources: In preparation for linking the future ICRF3 and Gaia optical reference frames, four lists of transfer sources (quasars that should be visible by both systems) were compiled by Observatory of Bordeaux personnel. Class 4, with 24 sources, had the weakest and least observed sources. We scheduled these 24 sources in R&D and RDV sessions. Some were detected in the R&Ds, and all were detected in the RDVs. Their fluxes were added to the *sked* flux catalog. These will be re-observed occasionally in future R&D and/or RDV sessions.
- Thermal Deformation Modeling: Thermal expansion can affect a VLBI antenna's height by as much as 20 mm. In Le Bail et al. (2013), we investigated the impact of thermal expansion, as well as the optimal time lags for steel telescope structures and concrete foundations, using the Nothnagel model (J. Geodesy, **83**, pages 787–792, 2009). We compared different solutions of the R1 and R4 sessions from January 2002 to March 2011 with and without the thermal expansion model and with different time lags. Thermal deformation modeling significantly improved the VLBI solutions, improving the baseline length repeatability on more than 75% of the baselines by more than 1 mm on average, and reducing the WRMS per station. The time lag for the steel structures was optimal when set to zero, one, or two hours. However, for concrete foundations, no sensitivity to time lag was found. We believe this is because the concrete foundations are much smaller than the steel structures. Also, preliminary results show significant correlations between 1) the maximum WRMS improvement and the height of the foundation, 2) the maximum WRMS improvement and the distance from the movable axis to the antenna vertex, and 3) the optimal time lag for the antenna and the antenna diameter.
- Nutation Analysis: We rehabilitated nutkal2012.f, a Fortran routine that uses the Kalman filter to regularize the nutation time series. The model is defined by a linear trend and specified harmonics, and the program includes an indicator of the quality of the estimate (goodness of fit).
- Analysis of LOD Time Series with the SSA: Variations in the temporal length-of-day (LOD) contain information on phenomena related to the continuous evolution of Earth processes: tidal energy dissipation and core-mantle coupling (decadal and secular) and meteorological and solar-lunar tide effects (annual and semiannual). We studied an LOD time series obtained from VLBI and extracted its principal components using Singular Spectrum Analysis (SSA) (Le Bail et al., 2014). After removing the long-term trend which explains 73.8% of the signal, three remaining components explain a further 22.0% of the signal: an annual and a semi-annual signal as well as a second trend. Using the complex demodulation method, we obtained the variations in the amplitudes of the annual and semi-annual components. We compared the Multivariate ENSO index (MEI) with these series and with the second trend obtained by the SSA. The correlations are significant: 0.58 for the annual component, -0.48 for the semi-annual component and 0.46 for the second trend.
- Troposphere Raytracing: We wrote a paper on the calculation of troposphere raytrace delays and the application of raytraced delay corrections. It will be submitted to the Journal of Geophysical Research. These delays were calculated by raytracing 3D refractivity fields computed from the NASA/GSFC

GEOS 5.9.1 numerical weather model. Repeatabilities were reduced for 70% of CONT11 baseline lengths and for 84% of CONT11 vertical site coordinates. We set up a raytracing service that provides raytrace delays for all VLBI sessions since 2000 at http://lacerta.gsfc.nasa.gov/tropodelays.

- Hydrology Loading: We wrote a paper on hydrology loading entitled, "Continental hydrology loading observed by VLBI measurements", which was submitted to Journal of Geodesy. It discusses the VLBI analysis results due to applying a hydrology loading series calculated from either 1) the GSFC GLDAS hydrology model or 2) GRACE (Gravity Recovery and Climate Experiment) mascons. We obtained a reduction in 1) baseline length repeatabilities for 80% of baselines, 2) site vertical repeatabilities for 80% of the sites, and 3) annual site vertical amplitudes for 90% of the sites.
- Space Geodesy Project Simulations: We are working with Erricos Pavlis (UMBC) to optimize the choice of a global network of co-located technique sites and specifically to decide where NASA should establish new sites. We have provided the VLBI observations and solution setup input for *Geodyn* SLR+VLBI+GPS combination solutions. Simulated observed VLBI delays consist of troposphere turbulence, clock, and observation noise contributions. We have done simulations of current observing networks of legacy antennas and are working on the simulations for future networks of broadband antennas, which are expected to grow to 15-20 antennas by around 2018.
- Second Epoch VCS Observations: A proposal to re-observe up to 2400 VCS (VLBA Calibrator Survey) sources was submitted to the VLBA and approved. The investigators are D. Gordon (PI), C. Ma, six other IVS members and two NRAO astronomers. This project was granted eight 24-hour sessions and will use the RDBE system at X- and S-bands with 16 32-MHz channels. The observations will run in 2014.

4 Software Development

The GSFC VLBI Analysis Center develops and maintains the *Calc/Solve* analysis system, a package of ∼120 programs and 1.2 million lines of code. During 2013, modifications were made to enable *Calc/Solve* to be compiled, loaded, and run on 64-bit machines. Additional modifications to allow it to be compiled with gfortran, instead of the Intel compiler, are underway.

Program *calc* was updated to version 11 for compliance with the IERS 2010 Conventions. *Calc11* uses the IAU2006/2000 Precession/Nutation model, a new ocean loading model (Hardisp) with 342 constituent tides, an ocean pole tide loading model, and improved high frequency EOP corrections. We also began work on a specialized version, *dcalc*, for use with the *difx* software correlator. *Dcalc* also contains a near-field delay model, based on the model of Sekido and Fukishima (J. Geodesy, **80,** pages 137–149, 2006), to allow better correlation of Earth satellites and planetary probes.

We continued development of the *vSolve* analysis program. The vgosDB part of the I/O module was improved and redesigned. Also, essential parts of the software were optimized to improve performance. Numerous comparisons of interactive *Solve* and *vSolve* have shown the two to be comparable. *vSolve* is now the standard tool for processing the IVS-R4 and IVS-INT sessions at GSFC.

We continued to develop and refine the *vgosDB* data format to store VLBI data. This year we concentrated on programs to reproduce all stages of the processing of Mark III databases. *vgosDBmake* takes correlator output and knits the files together into the new format. *vgosDBcalc* is analogous to *calc* in that it adds theoretical and partials to the vgosDB session. *vgosDBcal* reads the log files and adds cable cal and met data. Since *vSolve* can read the vgosDB format, we are now able to perform all stages of analysis starting with correlator output. We also developed the utilities *vgosDBview* to view and modify data in this format, and *vgosDBcompare* which will compare files in the new format and find the differences.

It is well known that the scatter of baseline length is larger than it should be, based on the formal errors of the *Solve* solutions. One possible explanation for this is the presence of unmodeled station dependent noise. We developed software to determine this noise. The software takes as input baseline length measurements from some set of sessions, for example CONT11. It then adds station-dependent-noise to the formal errors until the chi-square of the baseline scatter is approximately equal to 1.

Table 1 Staff members and their main areas of activity.

Ms. Karen Baver	Intensive analysis, monitoring, and improvement; software development; Web site development; quarterly nuvel updates.
Dr. Sergei Bolotin	Database analysis, *vSolve* development, ICRF3.
Dr. John Gipson	Source monitoring, high frequency EOP, parameter estimation, new data structure, station dependent noise.
Dr. David Gordon	Database analysis, RDV analysis, ICRF3, astronomical source catalogs, *calc/dcalc* development, quarterly ITRF updates.
Dr. Karine Le Bail	Time series statistical analysis (EOP, nutation, source positions), database meteorological data analysis.
Dr. Chopo Ma	ICRF3, CRF/TRF/EOP, VGOS development.
Dr. Daniel MacMillan	CRF/TRF/EOP, mass loading, antenna deformation, VGOS and SGP simulations, VLBI/SLR/GPS combinations.
Mr. David Eriksson	Mass loading, troposphere raytracing (intern).
Mr. Tobias Forsberg	Station stabilities, vgosDB development (intern).
Ms. Julia Ringsby	vgosDB development (intern).
Mr. Ronny Videkull	vgosDB development (intern).
Ms. Emma Woxlin	Station stabilities, vgosDB development (intern).

5 Staff

During 2013, the Analysis Center staff consisted of one GSFC civil servant, Dr. Chopo Ma, six NVI, Inc. employees who work under contract to GSFC, and five temporary student interns from Chalmers University of Technology (Sweden). Dr. Ma oversees the GSFC VLBI project for GSFC and is also the IVS co-representative to the IERS. Dr. John Gipson is the GSFC VLBI Project Manager as well as the IVS Analysis Coordinator. Table 1 lists the staff members and their main areas of activity.

6 Future Plans

Plans for the next year include ICRF2 maintenance, second epoch VCS observations, preparations for ICRF3, participation in VGOS development, continued development of *vSolve* and the new vgosDB data format, upgrade of program *dcalc*, and further research aimed at improving the VLBI technique.

References

1. K. Baver and J. Gipson, “Refining the Uniform Sky Strategy for IVS-INT01 Scheduling”, Proceedings of the 21^{st} Meeting of the EVGA, N. Zubko and M. Poutanen (Editors), pages 205–209, 2013.
2. S. Bolotin, K. Baver, J. Gipson, D. Gordon, D. MacMillan, “Status of nuSolve”, Proceedings of the 21st Meeting of the EVGA, N. Zubko and M. Poutanen (Editors), pages 77-80, 2013.
3. K. Le Bail, J. M. Gipson, J. Juhl, D. S. MacMillan, “Optimal time lags to use in modeling the thermal deformation of VLBI Antennas”, Proceedings of the 21^{st} Meeting of the EVGA, N. Zubko and M. Poutanen (Editors), pages 165–168, 2013.
4. K. Le Bail, J. M. Gipson, D. S. MacMillan, “Quantifying the correlation between the MEI and LOD variations by decomposing LOD with Singular Spectrum Analysis”, Proceedings of the IAG General Assembly, Melbourne, Australia, June 28–July 2, 2011; IAG Symposia, Vol. 139; Rizos, Chris; Willis, Pascal (Editors), pages 473-480, 2014.
5. David Gordon, Chopo Ma, Dan MacMillan, Sergei Bolotin, Karine Le Bail, and John Gipson, “Effects of ICRF2 on the TRF, CRF, and EOP”, Reference Frames for Applications in Geosciences, IAG Symposia, Vol. 138; Z. Altimimi and X. Collilieux (Editors), pages 175-180, 2013.
6. C. Ma, D. MacMillan, S. Bolotin, K. Le Bail, D. Gordon, and J. Gipson, “Comparison of Realizations of the Terrestrial Reference Frame”, Reference Frames for Applications in Geosciences, IAG Symposia, Vol. 138; Z. Altimimi and X. Collilieux (Editors), pages 51-56, 2013.